The ATLAS Silicon Pixel Sensors

Sally Seidel, Igor Gorelov, Martin Hoeferkamp, Steve Worm

University of New Mexico, Albuquerque

CDF RunIIb Pixel Meeting
September 20, 2000
FNAL

The University of New Mexico

the new mexico center
for particle physics

Contents

- Overview of the pixel detector system
  - requirements
  - layout
- Sensor design
  - concept
  - isolation technique
  - bias grid
  - radiation hard sensors
- Quality assurance
  - goals
  - prototype production wafers
  - I-V measurements
  - measurements on test structures
  - statistics for Prototype 2 wafer measurements
- Test beam studies
  - charge collection
  - depletion depth
  - efficiencies
  - spatial resolution
- UNM capabilities
- CDF pixels
- Summary

Overview - requirements ...

LHC environment

- High Luminosity 10^{34} $cm^{-2}s^{-1}$
  - 25 interactions/bunch crossing
  - high event multiplicity
  - 40 MHZ Bunch Crossing freq.
  - High radiation region close to I.P.
    - damage equivalent dose is up to 10^{15} n_{eq}/cm^2 in 10 years of LHC operation
    - even higher damage in innermost layer - 10^{15} n_{eq}/cm^2 in 5 years

Robust pattern recognition

- low ambiguity - space points
- low occupancy - high granu-larity

Excellent transverse impact parameter resolution and very good 3D-vertexing

- $\sigma_{r-\phi} = 12\ \mu m$, $\sigma_z = 60\mu m$

Excellent b-tagging efficiency of ~50% with rejection factor against light quark/gluon jets of ~100.

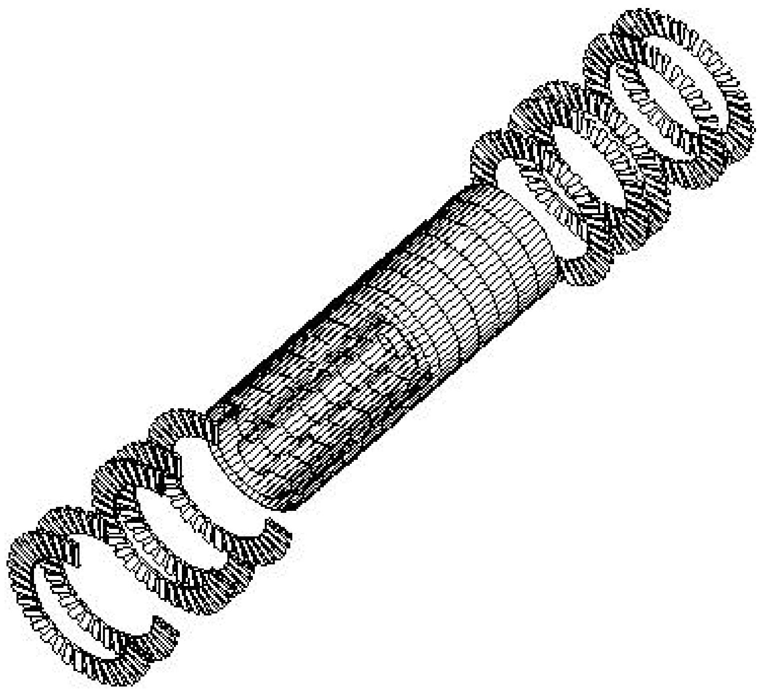
Good b-triggering.

Overview - requirements ...

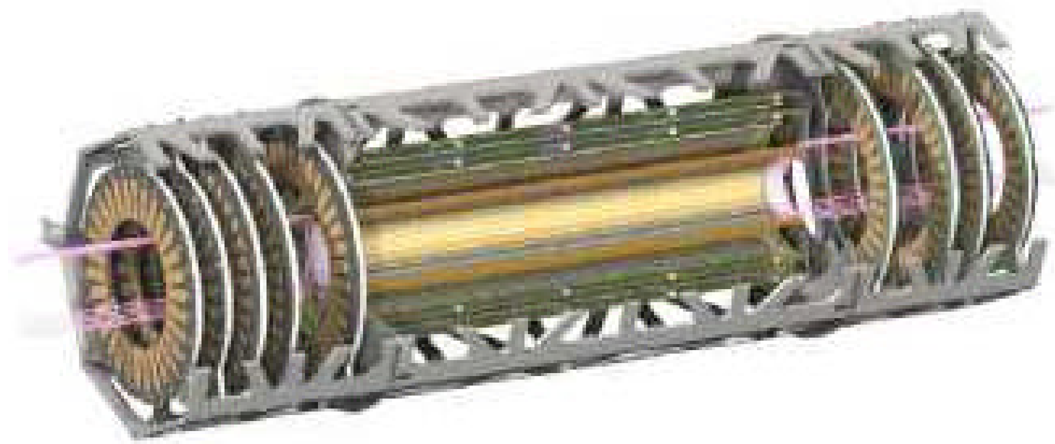
Pixels have ...

- very small capacitance/pixel due to **high segmentation** - good S/N
  - pixel areas 400μm vs strip length of 10cm (~<1/200)
  - the input cap. load to FE ~200-300fF incl. tot. det-r and parasitic capacitances (10μm betw. det-r and FE chip planes)
  - much lower noise and S/N = 19Ke/(noise 300e+thr.rms 200e)~50 for 250μm Si . After lifetime fluence S is expected to be ~6Ke
  - work thresholds of 3Ke …2Ke (>5σ)
- rad. hardness
  - high breakdown voltages of ~600V made possible with 'moderated p-spray' isolation technique
  - n^+- implants on n substrate
  - work at partial depletion for 'n^+-on-n' sensors (no p- sensitive areas !) - still with 6Ke signals and 2Ke thresholds
  - oxygenation of Si reduces N_{eff} and V_{depl}
  - lower (w.r.t. to strips) leakage currents - worst case at lifetime fluences is 15nA at -6^{o}C
  - lower power budget of ~40μW/pixel

Overview - layout ...



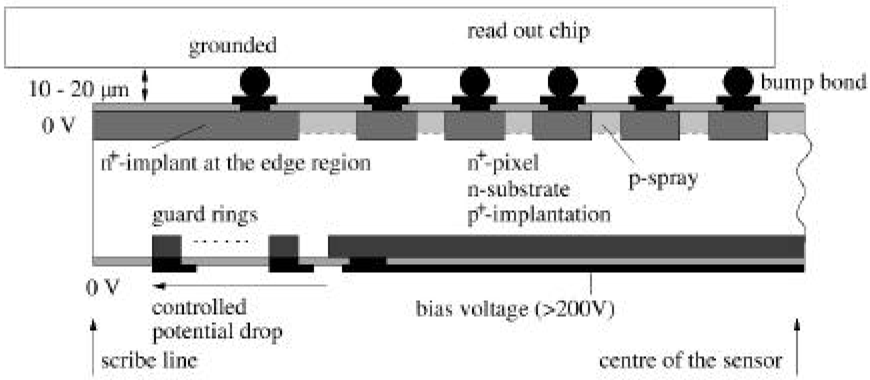
- **Barrel: 3 layers**
  - radii: 12.7 cm, 9.3 cm, 4.15cm (B-layer)
- **2 x 5 disks made of sectors**
- **2228 modules**
  - each module with 47232 pixels
  - 1.4×10^8 pixels
  - 2.3 m^2 of silicon
- **1.8% X_0 per layer**
- **coverage up to h = 2.5**

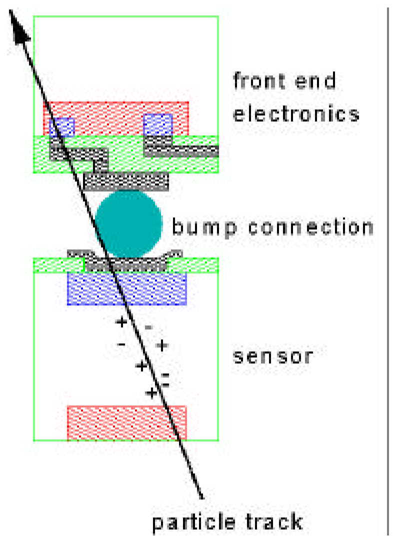


- **Support structure**
  - flat panel carbon composite
  - light weight

I.Gorelov, M.Hoeferkamp,
S.Seidel, S.Worm, Univ. of N.M.

Sensors - concept ...





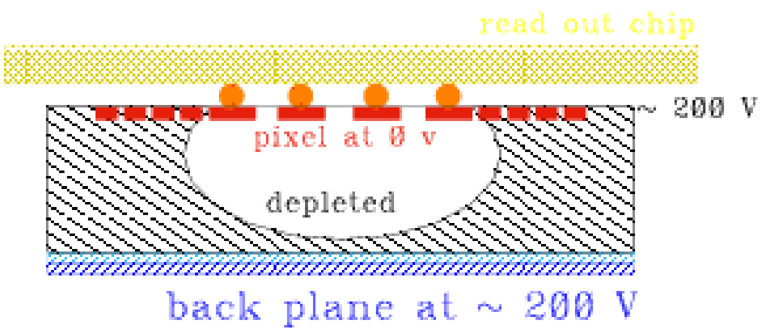
- n^+ pixels on n substrate
  - substrate thickness 250mm (200mm for B-layer), wafer diameter - 4 inch.
  - before irradiation: junction on back side with p^+ implantation
  - irradiated detectors: bulk type inversion - junction on pixel side
- pixel cell 50 x 400 mm^2
  - defined by the electronic cell size
  - with a pitch of 50mm
  - 12mm opened area for bump bonds
- bump bonding
  - IZM: PbSn bumps
  - Alenia Marconi Systems: In bumps
  - 6-20 mm diameter
- bias voltage applied to p^+ side
  - pixels held at ground
  - low potential difference between sensor and electronics

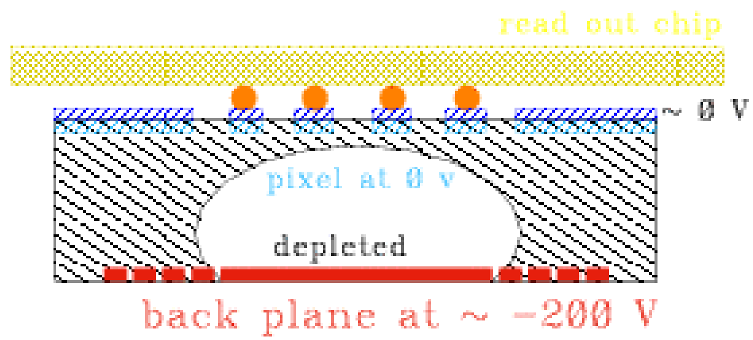
Sensors - concept ...

before irradiation:

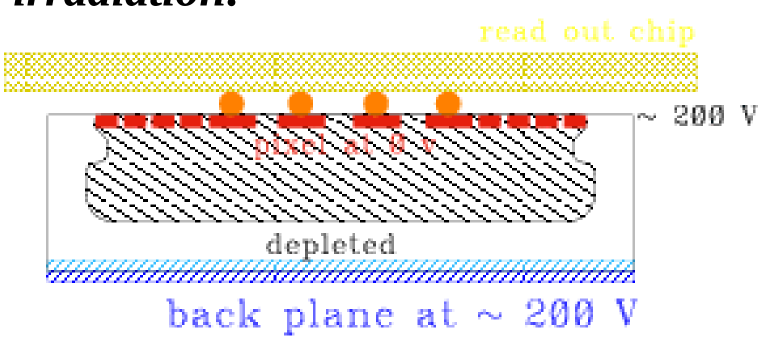
(not selected)
p-on-n

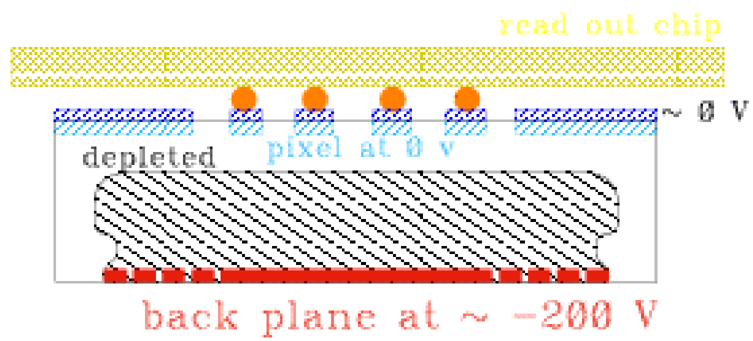
ATLAS option
n-on-n





after irradiation:





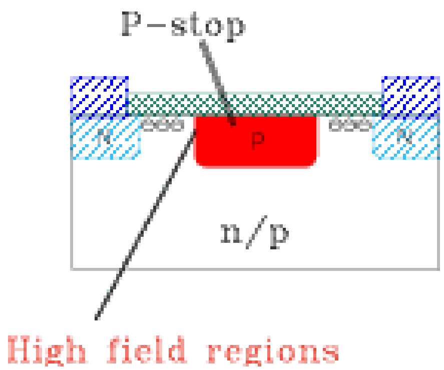
- *have to be operated (almost) fully depleted*
- *potential drop on the read out side*
- *only single sided processing necessary*

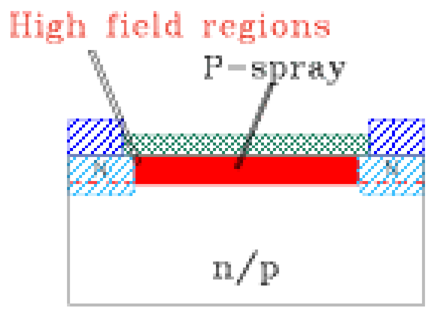
- *can be operated partially depleted*
- *potential drop on the back side*
- *double sided processing needed*

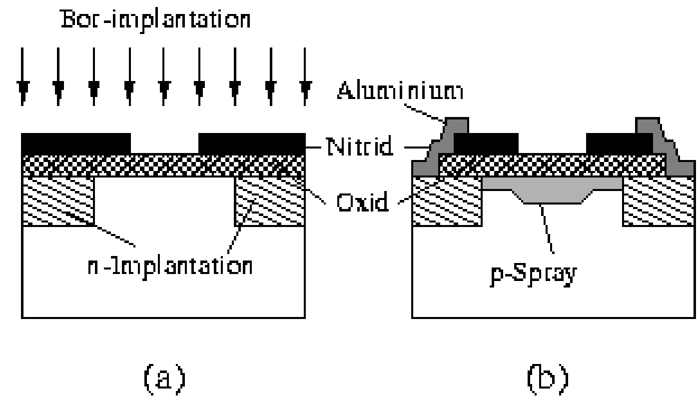
Sensors - isolation techniques

During irrad.: increase of E-fields due to increase of ox.-Si charge;
increase of effective doping concentration N_{eff}

p-stop	*p-spray*	*moderated p-spray*



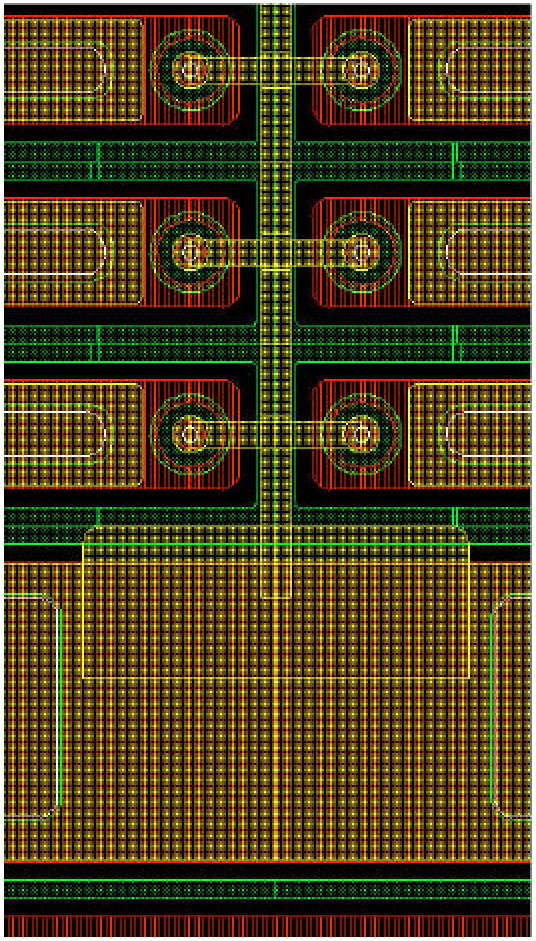




before irr. :	*low E-field*	*high E-field*	*low E-field*
after irr. :	*high E-field*	*low E-field*	*low E-field*

Sensors - testability, bias grid

- ***The need to test sensor alone, before bonding with FE chip***
- ***bias grid on a sensor of a p-spray design***
  - ***to apply uniform bias voltage to all pixels on a tile sensor***
  - ***n^+ -implanted path throughout array and special n^+ -dots are formed for every pair of pixels of neighboring columns***
  - ***pixels get biased through a "punch-through" mechanism***

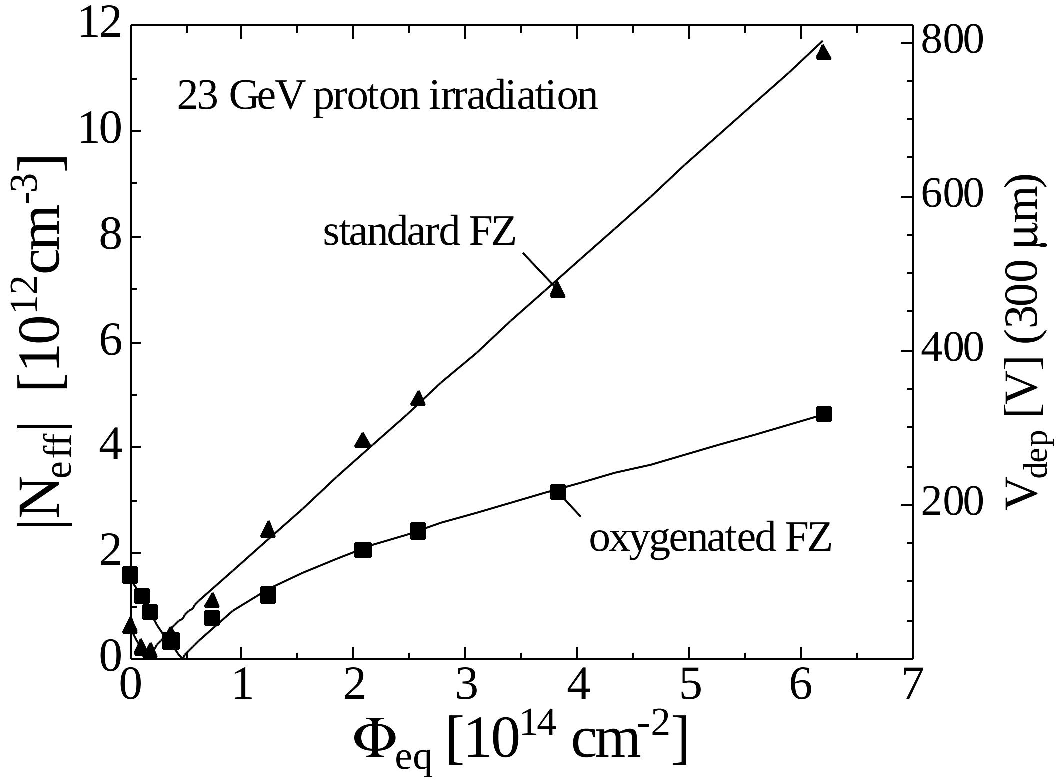


Sensors - radiation hard

Oxygenated sensors

- *based on the studies of RD48 (ROSE) Collab.*
- *reduce effective doping dose*
  - *lower depletion voltage*
  - *improvement of charge collection after irradiation*
  - *lower bias and leakage current*
  - *extended detector lifetime*
- *Oxygenated sensors prototypes produced*
  - *O_2 thermal diffusion - Si to be kept 24 hrs at 1150°C in pure O_2*
  - *already irradiated up to 5.6x10^{14} n_{eq}/cm^2*
  - *currently data are collected in the test beam to measure:*
    - *depletion depth vs V*
    - *charge collection*
    - *efficiency*
    - *and resolution*

A factor of ~2 lower bias voltage for oxygenated sensors after ~10^{15} n/cm²



Ref.: M.Moll, PhD thesis, Hamburg 1999

Quality Assurance - goals

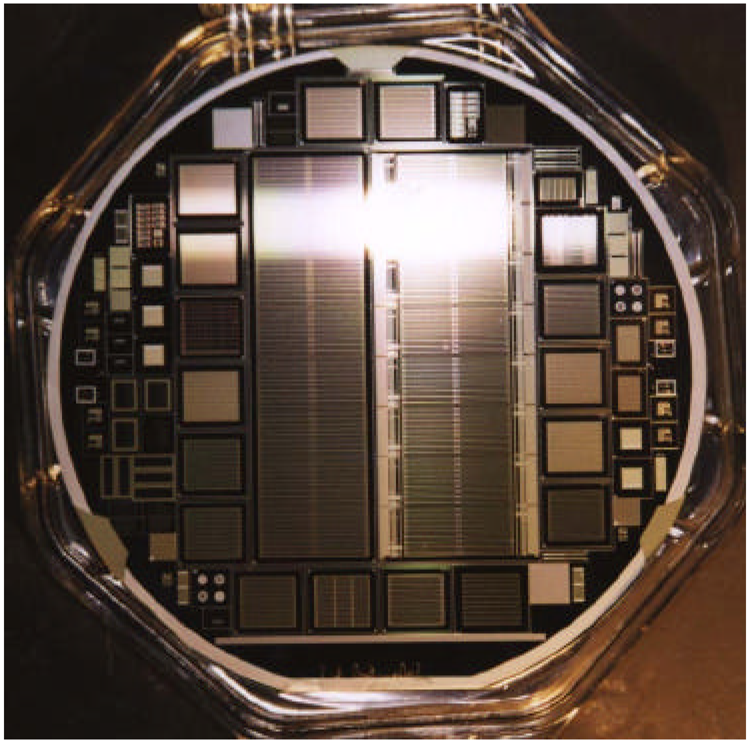
QA procedure for sensors at a mass production stage to guarantee a high sensor quality.

All wafers:

- visual inspection
- wafer thickness and flatness
- I-V of each tile and 'single chip' to measure V_{bd}

Detailed tests on representative samples using special test structures:

- monitor rad. bulk damage
  - I-V of 'mini chips' before and after irrad. from every batch
  - I-V,C-V on diodes- V_{depl} and resistivity



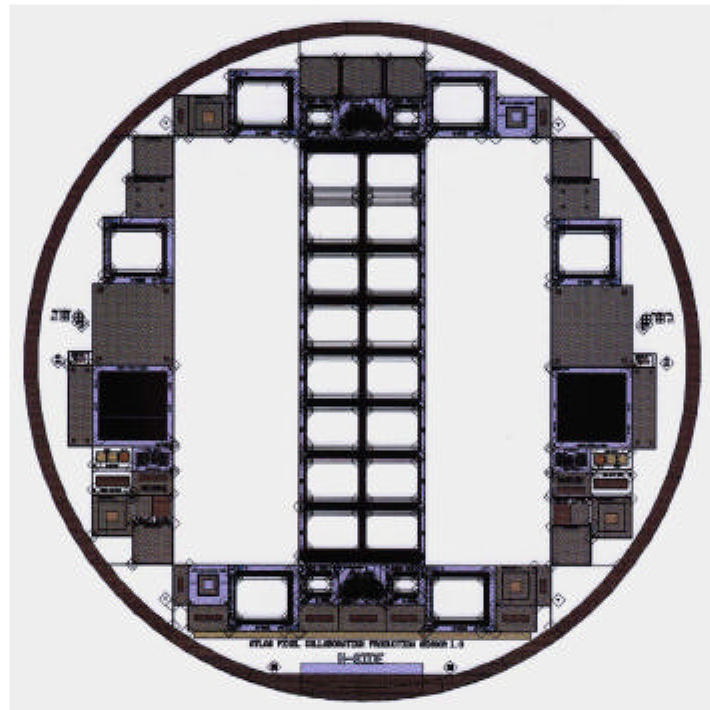
Prototype 1 Wafer with two tiles, also in the left bottom corner is seen the test structure with four circles - two MOS pads and two GateControlDiodes ...

Quality Assurance - goals ...

- *monitor ionizing damage with 50kRad low energy electron dose - positive charge build up in oxide layers.*
  - *MOS pads - oxide breakdown (I-V curve) voltage; capacitance C-V measurement to determine flat-band voltage V_{FB}*
  - *I-V with gate control diodes, GCD, to monitor oxide-Si interface current around V_{FB} before and after irrad.*
  - *MOSFET test field - measurement of n- to p- type inversion voltage $V_{threshold}$ to calculate the p-spray dose (using also measured above V_{FB}) - before and after irrad.*

The Production Wafer (gds file)

- *4 inch diameter*
- *with three tiles to be used as the pixel sensors*
- *and a number of test structures*



I.Gorelov, M.Hoeferkamp, S.Seidel, S.Worm, Univ. of N.M.

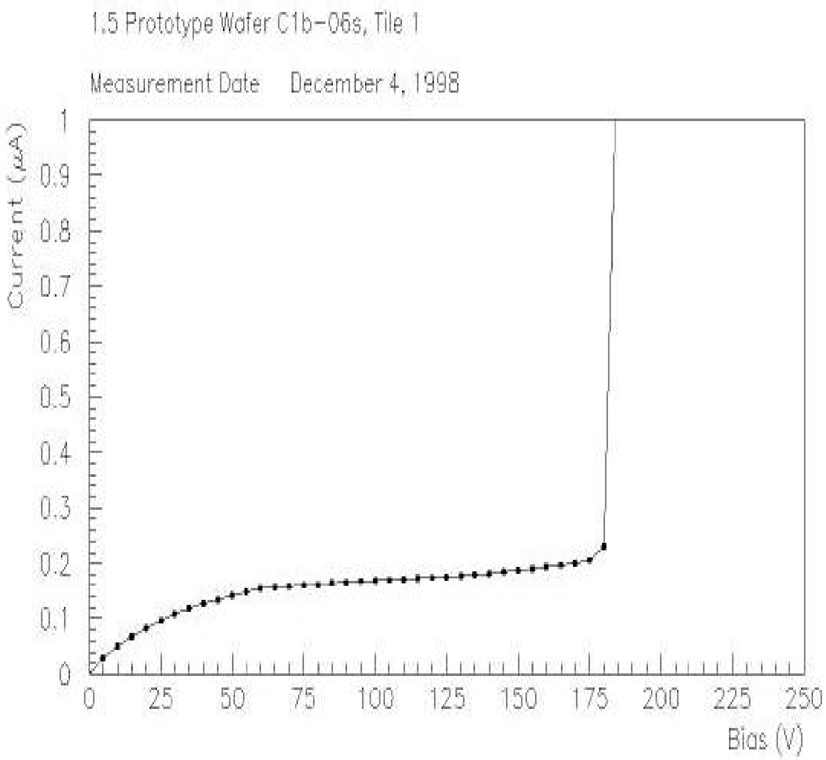
Quality Assurance - typical I-V's for non-irradiated tiles

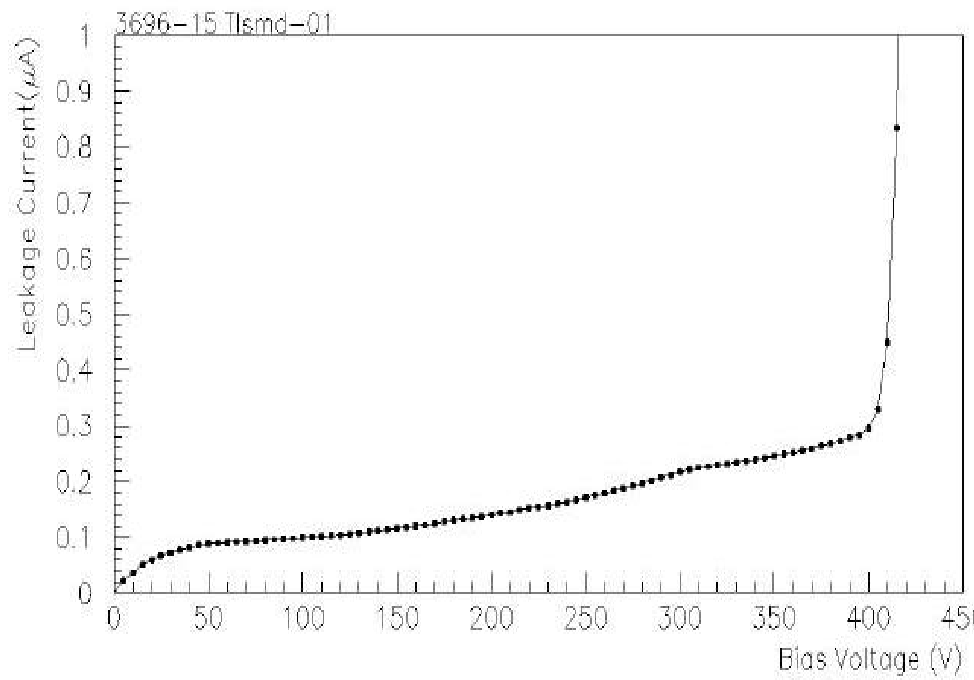
Breakdown voltage for Tile sensor with normal p-spray of Prototype 1.

$V_{bd} = 180$ V

Breakdown voltage for Tile sensor with moderated p-spray of Prototype 2.

$V_{bd} = 410$ V



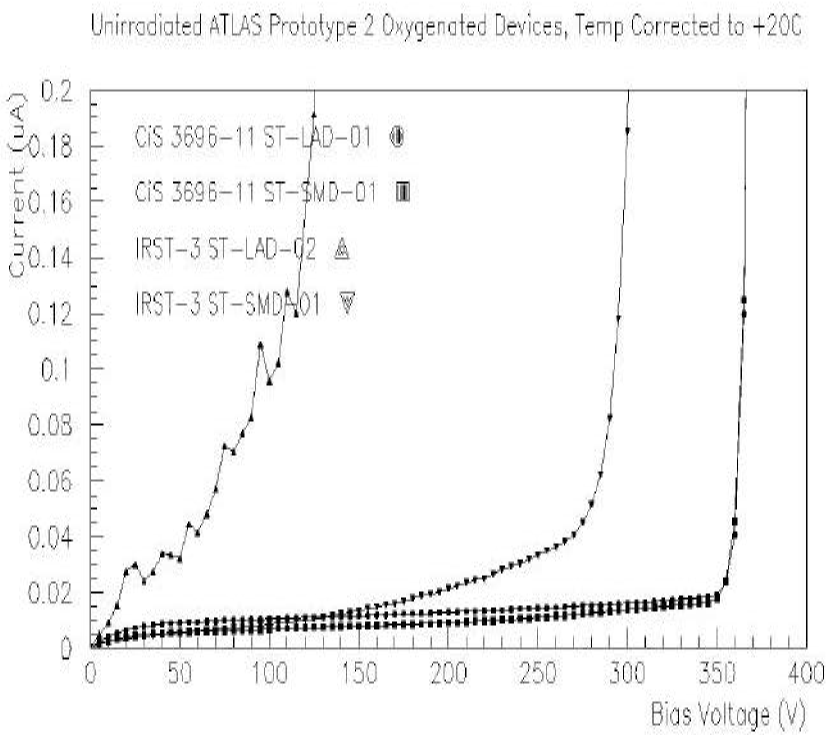


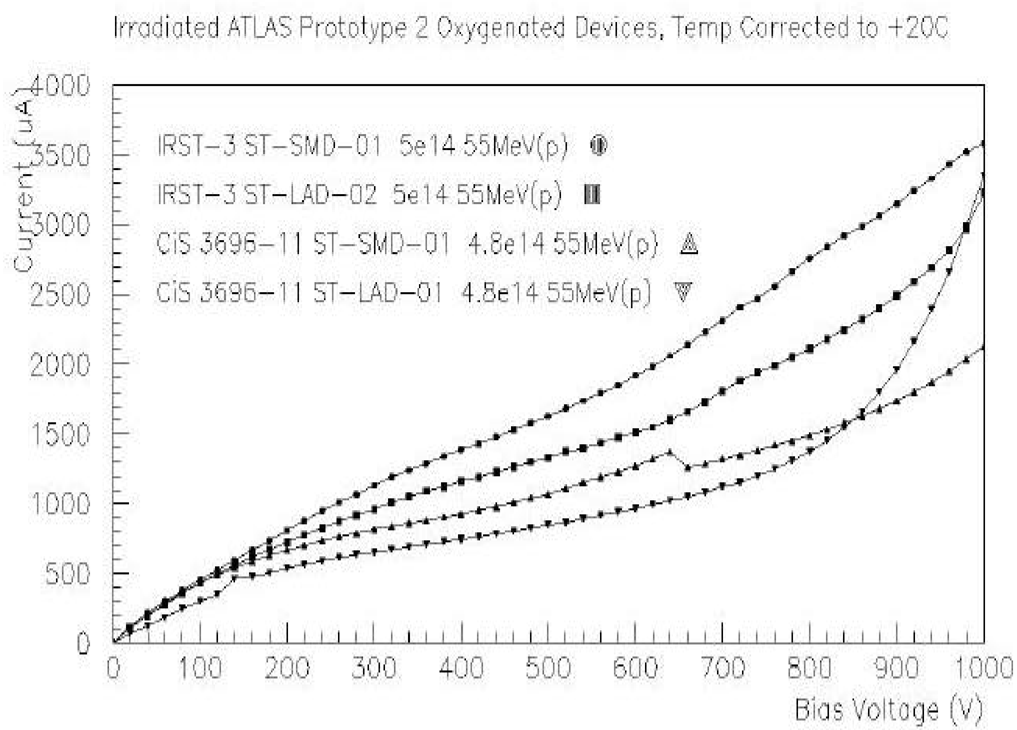
Quality Assurance - V_{bd} for irradiated vs non-irradiated SC

Tile-like topology 'single chip' sensors (1/16 scale of the tile), Prototype 2, non-irradiated. Vendors - CiS and IRST.

Oxygenated silicon.

The same sensors irradiated to $9*10^{14}$ 1MeV n/cm^2. Vendors - CiS and IRST.



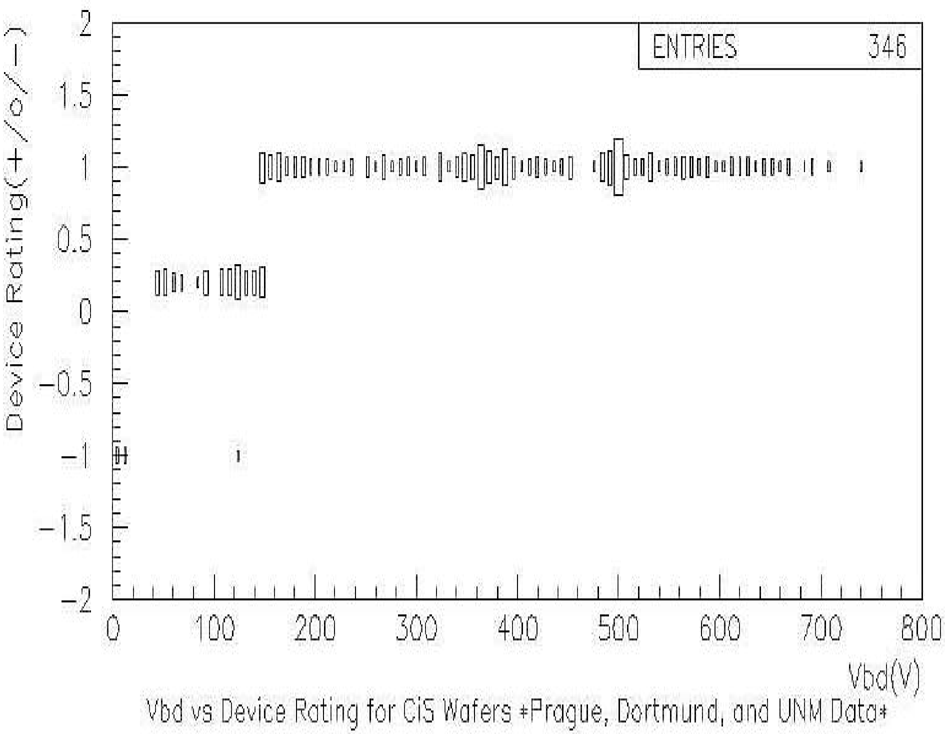


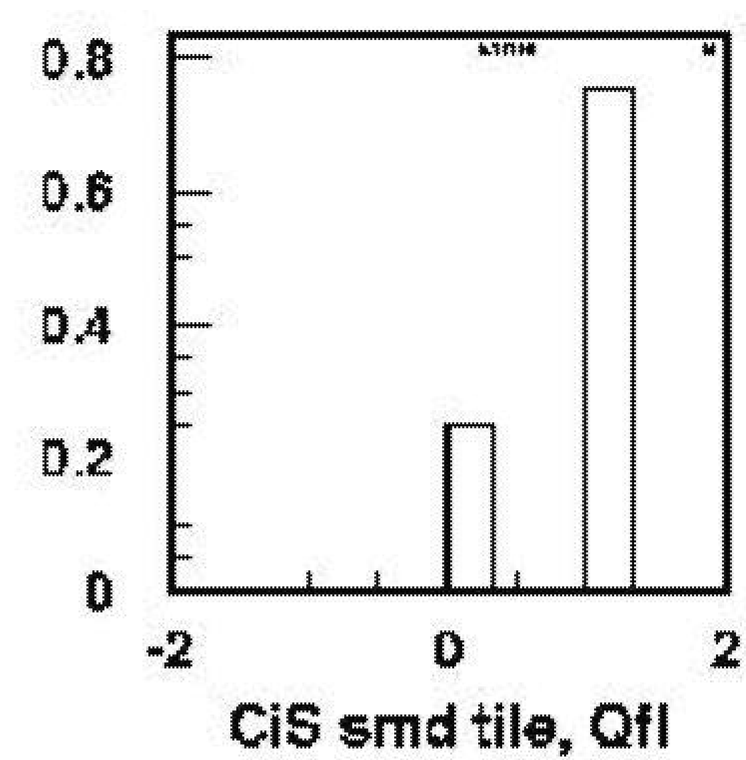
Quality Assurance - statistics for Prototype 2 measurements

Statistics collected over the labs of ATLAS Pixel Collab. For Prot.2 tile sensors classified by Q_{flag} .

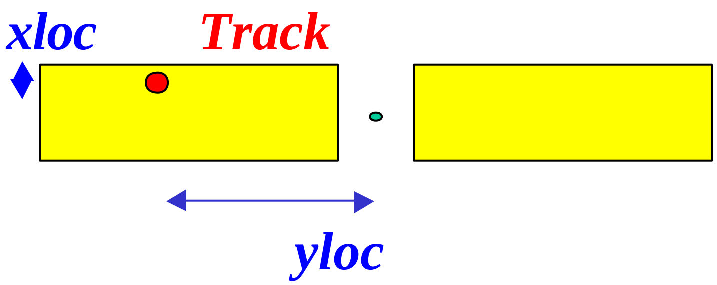
Q_{flag}	-1	0	+1
V_{bd}	<50V	(50…150)V	>150V

Percentage of Prototype 2 tiles for every quality flag Q_{flag} = -1 , 0, +1 .
"Small Dot" design.

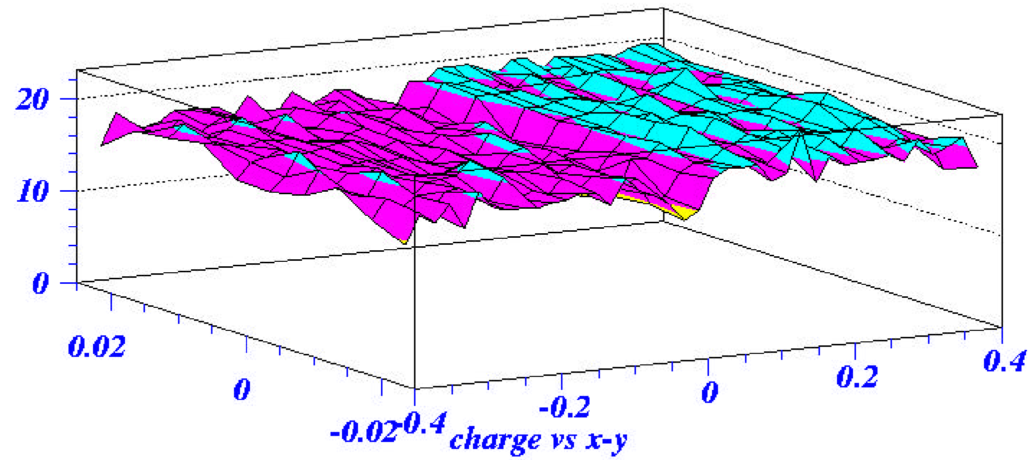




Beam Test Studies - charge collection

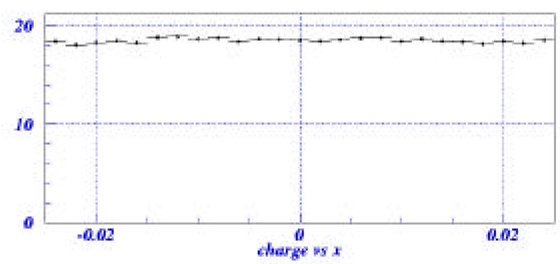


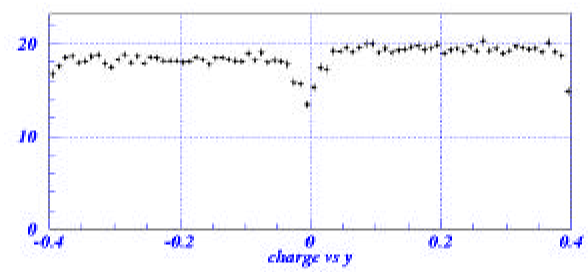
Prototype 2 wafer
Oxygenated - V_{bias} -400 V
Fluence 5.6 10^{14} n_{eq}/cm^2



Charge collection uniformity

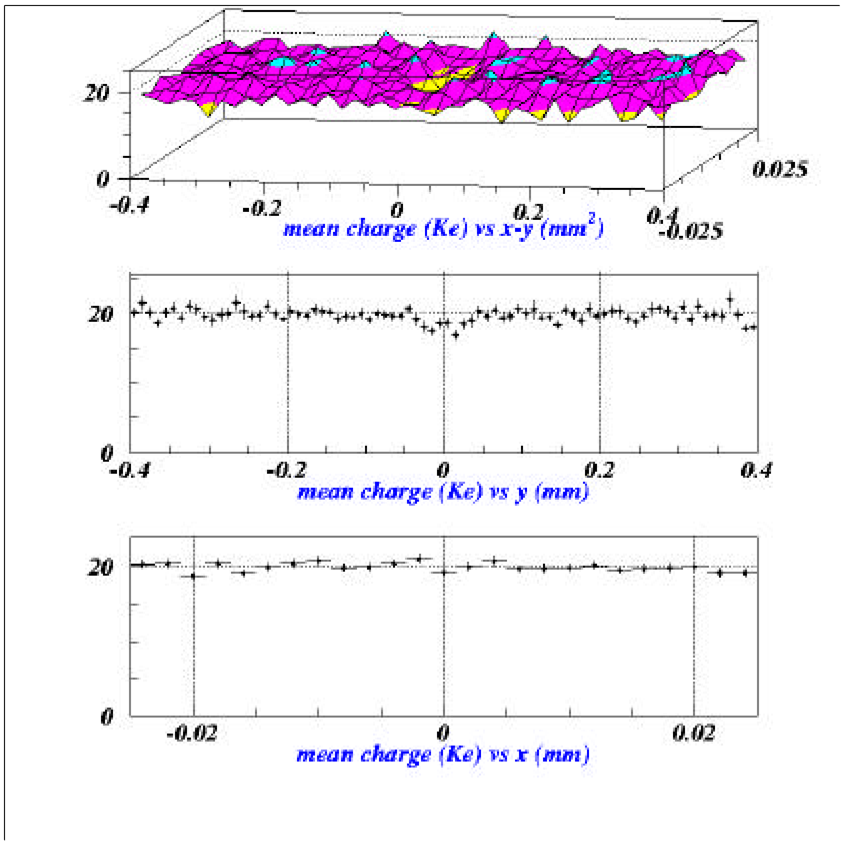
- *track position extrapolated to the pixel detector*
- *for each position bin the average cluster charge is computed*
- *the signal is of ~18000e⁻*



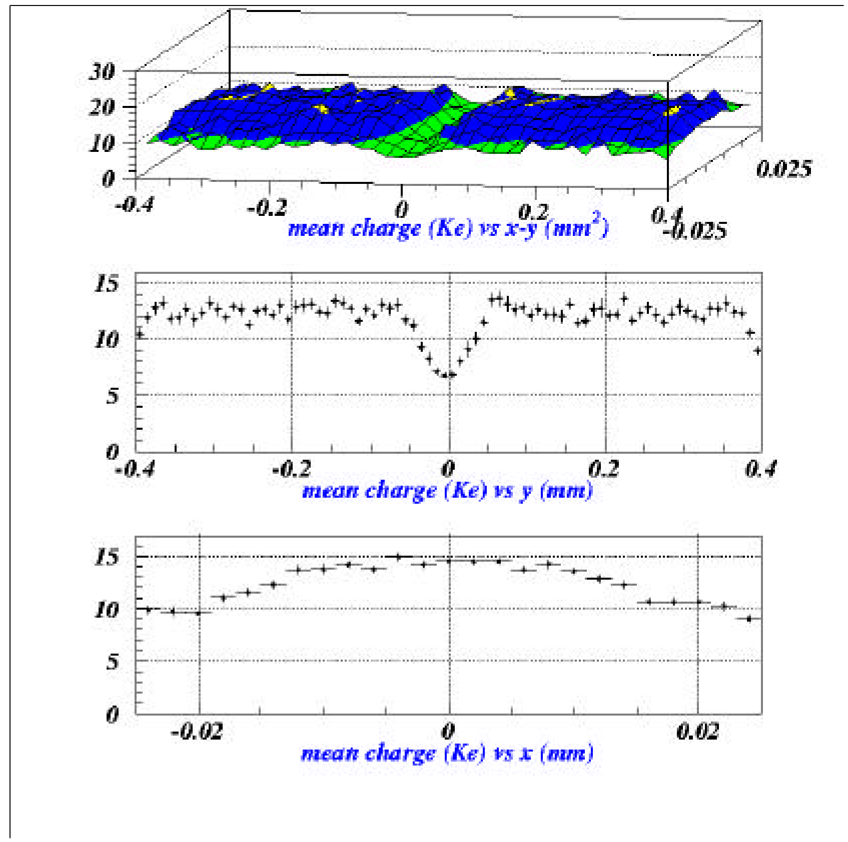


Beam Test Studies - charge collection

Prototype 2 wafer
Not Oxygenated - V_{bias} -150 V
Fluence 0



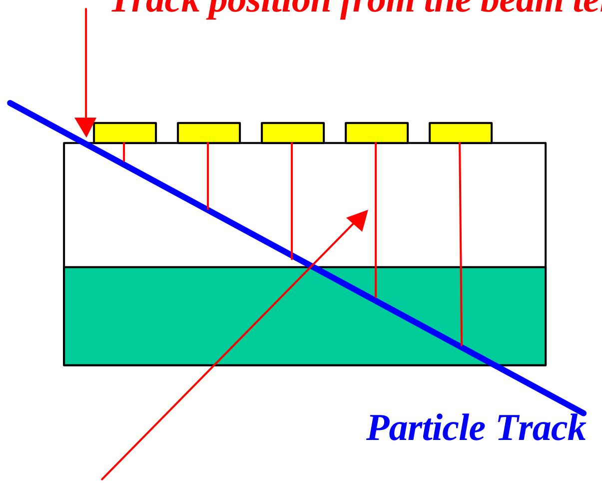
Prototype 1 wafer
Old Design (not oxy)- V_{bias} -600 V
Fluence 10 10^{14} n_{eq}/cm^2

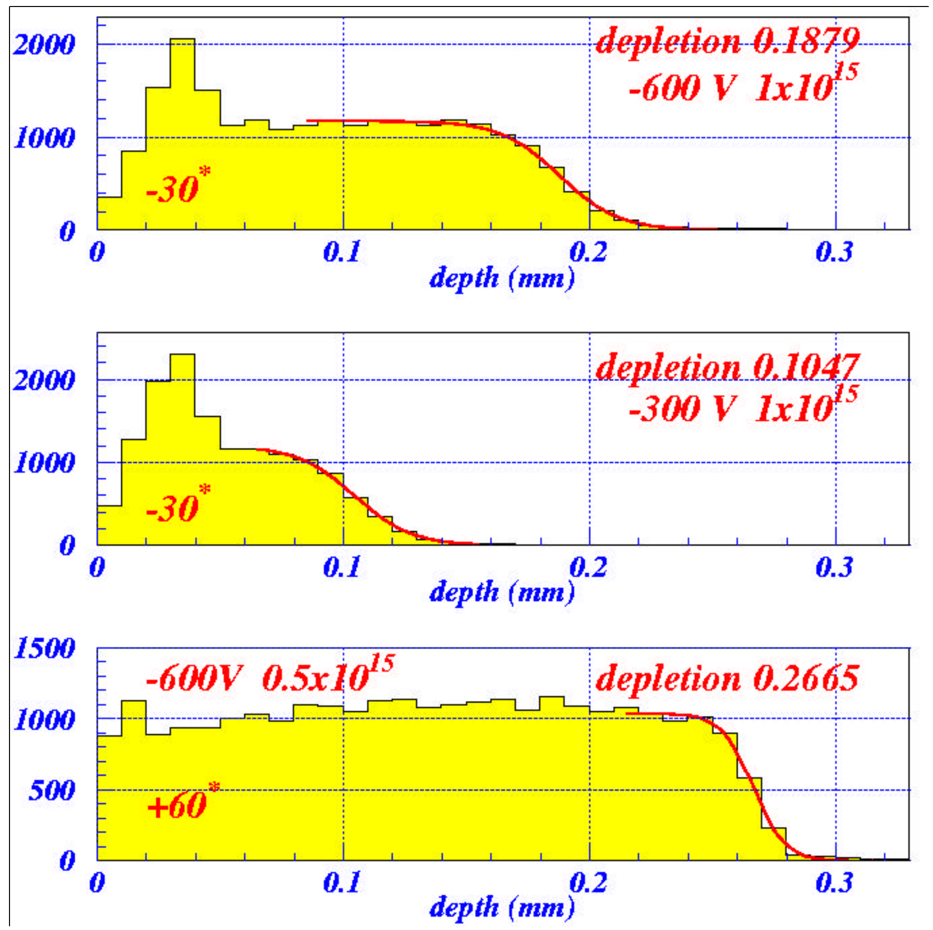


I.Gorelov, M.Hoeferkamp,
S.Seidel, S.Worm, Univ. of N.M.

Beam Test Studies - depletion

Depletion depth





- After 10^{15} n_{eq}/cm^2 the depletion depth is 190 mm @ -600 V
- PRELIMINARY: oxygenated sensor (250 mm thick) fully depleted @ -400 V after 5.6 10^{14} n/cm^2

I.Gorelov, M.Hoeferkamp,
S.Seidel, S.Worm, Univ. of N.M.

Beam Test Studies - Efficiency (sensor and analog part)

Efficiency losses:

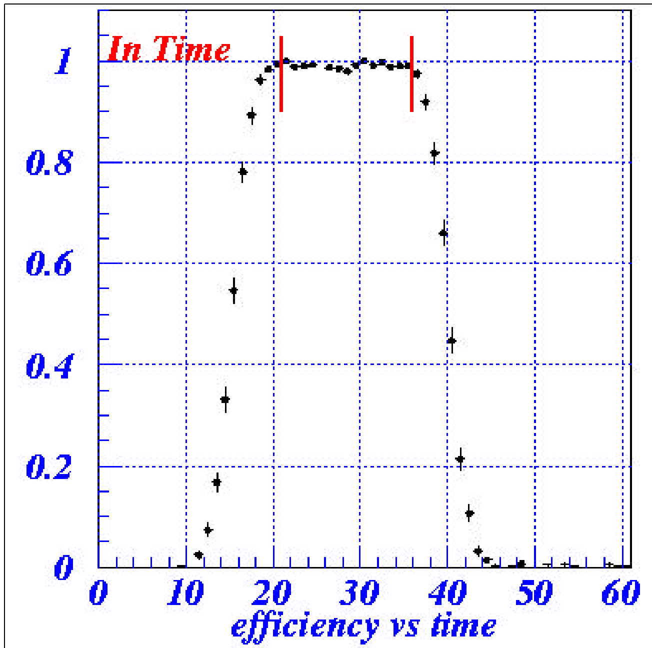
- missing hits
  - low pulse height below threshold
  - dead time
- wrong bunch crossing
  - time walk

Efficiency measurement:

- look for hits where expected
- measured as a function of the particle-clock time phase

not Irradiated - Thr. 3 Ke

efficiency	99.1	Losses	0.9
1 hit	81.8	0 hits	0.4
2 hits	15.6	not matched	0.1
>2 hits	1.7	not in time	0.4



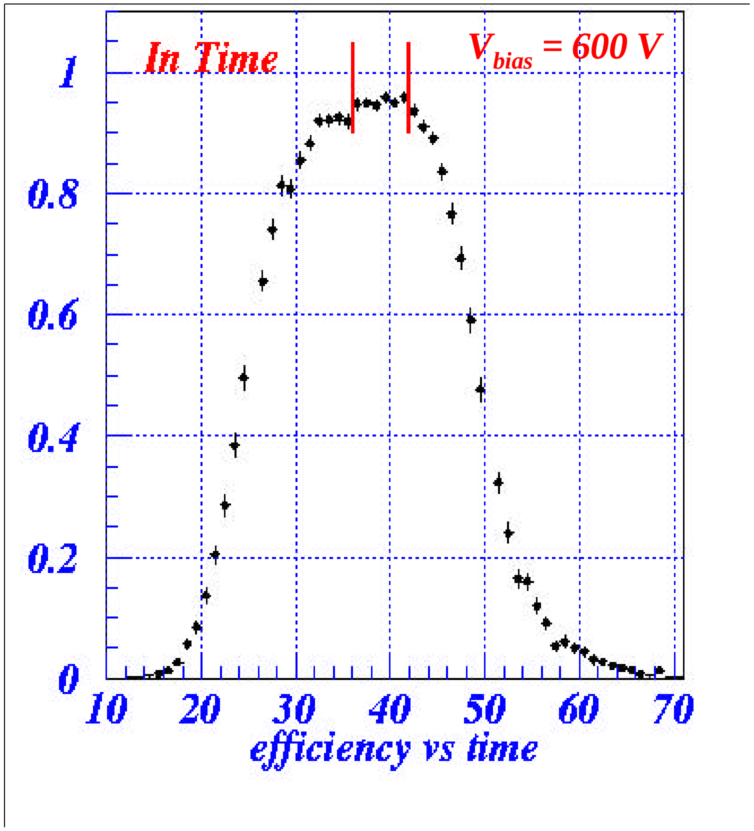
Efficiency (sensor and analog part)

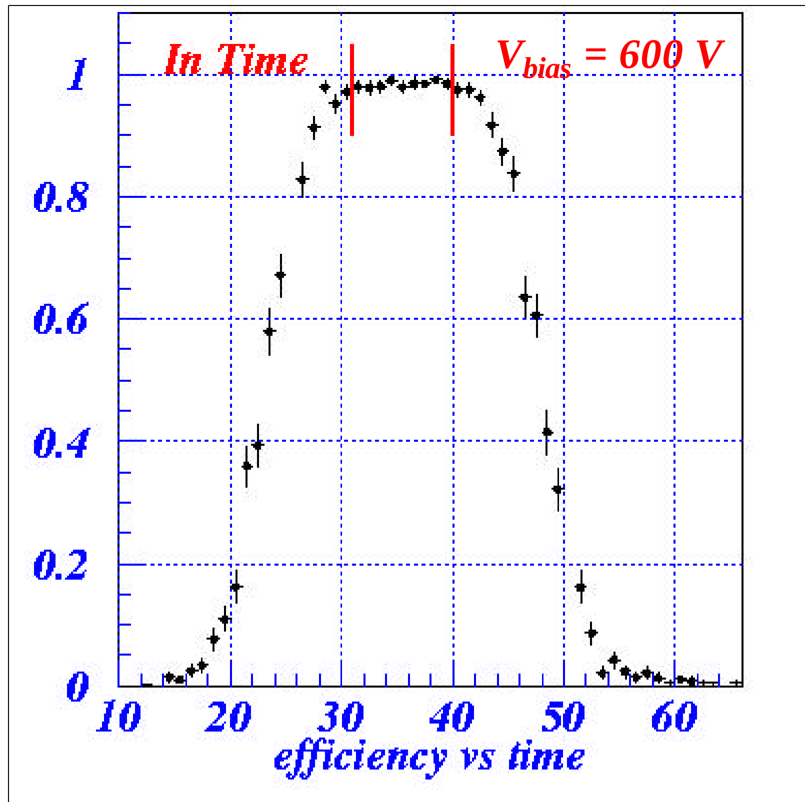
Irradiated 10^{15} n/cm^2 - Thr. 3 Ke

efficiency	95.3	Losses	4.7
1 hit	86.3	0 hits	2.2
2 hits	7.6	not matched	0.1
>2 hits	1.4	not in time	2.4

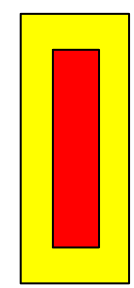
Irradiated 10^{15} n/cm^2 - Thr. 3 Ke

efficiency	98.4	Losses	1.6
1 hit	94.2	0 hits	0.4
2 hits	3.1	not matched	0.0
>2 hits	1.1	not in time	1.2



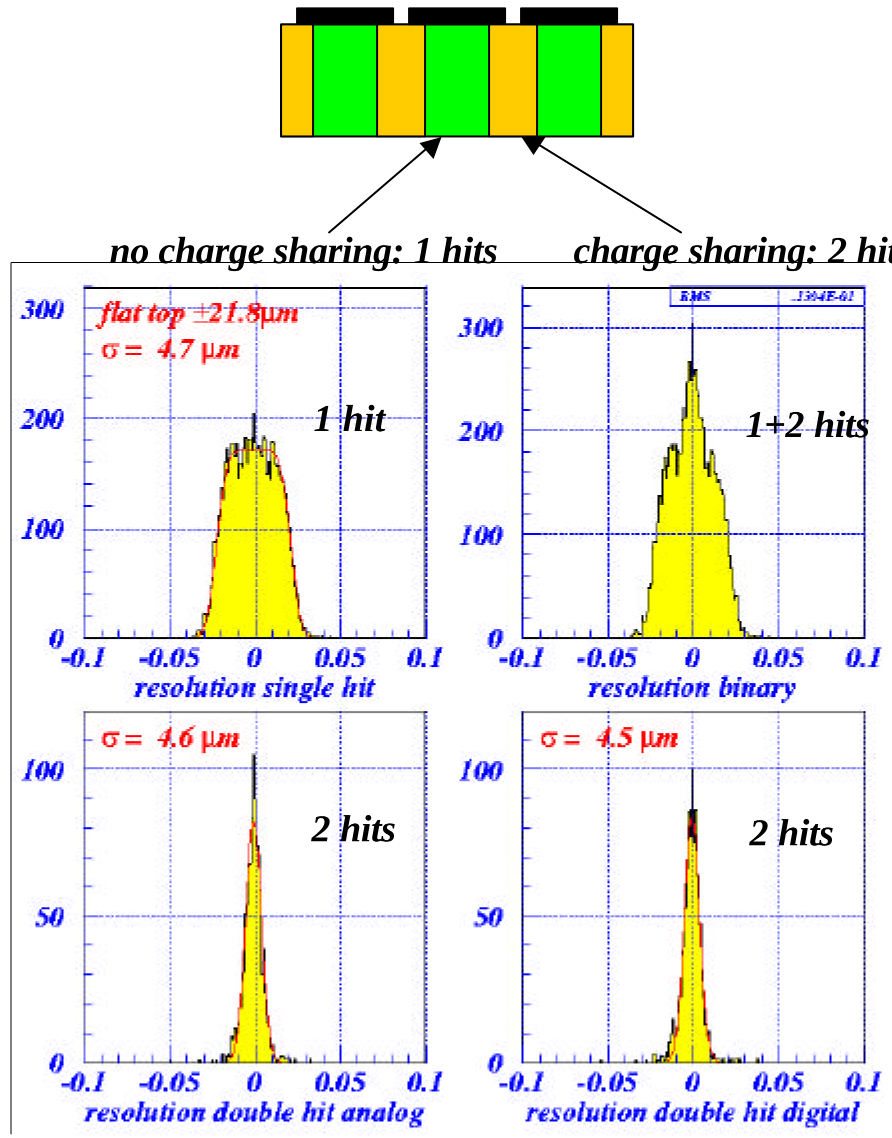


X-Y cut off pixel edges applied



Beam Test Studies - Spatial Resolution

- *Resolution at 0^o (Thresh. 3 Ke)*
  - *depends on the ratio: 2 hits to single hits*
  - *sharing is within ± 3 mm for 200 mm thick sensors*
  - *~ 15 % of double hits*
- *At larger angles the charge sharing region extends*
- *Depleted region extension affects the multiple hits rate (radiation damage)*
- *Magnetic field modifies charge sharing (Lorentz angle)*
- *Analog measurement of the charge (ToT) improves resolution*



UNM pixel laboratory...

- *People: 1 electronic engineer, 3 physicists, several students.*
- *Design: Cadence software and installation of a Sun workstation in progress*
- *Test: clean room, probe stations and test equipment for full ATLAS pixels QA measurement plan*
- *Expertise:*
  - *CDF SVX II strip detector development and tests*
  - *ATLAS Pixel Sensor Prototype design and tests*

CDF -specific Pixel Sensors - management issues ...

- ***P-spray patent issues - MPI at Muenchen lab and ATLAS Collab.***
- ***cost estimate per wafer - communicate with CiS, TESLA and ATLAS Pixel Collab.***
- ***Design baseline - six ATLAS-like half tiles per wafer***
  - ***define the cell size to be determined by FE chip (bump- bonded with sensor)***
- ***Quantities - depends on sharing of a wafer area with other interested parties, approximately 50-150 wafers for late 2001***
  - ***possible overlap with ATLAS pixels production schedule***

Summary

- *The ATLAS pixel sensor design with rad. hardness up to* ~10^{15} n/cm^2 *fluencies ensured is ready.*
- *The production QA plans have been developed and UNM lab facilities are ready for production testing.*
- *CiS, Seiko, IRST and TESLA produced prototype wafers*
- *UNM can provide CDF Collaboration with a necessary experience*